Gray-Scale Lithography for Sloped-Surface 3-D MEMS Structures

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Microfabrication techniques that originated from the IC community typically yield 2-D extruded geometries or structures with limited angles due to crystallographic orientation. Gray-scale lithography in MEMS is capable of generating a gradient height profile in photoresist, and subsequently in silicon, after deep reactive ion etching (DRIE) or other dry etching techniques. Our work has sought to establish this 3-D microfabrication capability at LLNL. Gray-scale lithographic techniques previously reported in the literature were used to baseline and calibrate arbitrary sloped-surface, 3-D microstructures at LLNL.

Typically, photolithographic processes involve a photomask with only an opaque “dark field” and a transparent “clear field,” resulting in 2-D features with relatively straight sidewalls in the photoresist. The gray-scale technique is performed by using a photomask with multiple, discreet “gray-levels” or with pixilated features to locally modulate the intensity of UV light used in the standard photoresist exposure process. This results in locally varied photoresist exposure and correspondingly varied depth/thickness upon wet chemical development. After DRIE, the 3-D depth profile is transferred to the silicon substrate and altered, based on the etch selectivity to silicon versus photoresist. By varying the optical density and spacing of the gray levels on the photomask, an arbitrary angle in the silicon microstructure can be achieved. This capability will enable a whole new class of microstructures not previously considered manufacturable at LLNL.

Project Goals

The result of this work will be the capability to fabricate arbitrary angle, sloped-surface, 3-D microstructures. Deliverables include:

1. a well-defined process for fabricating 3-D MEMS structures (sloped surfaces) of arbitrary angle based on a combination of parameters such as photomask optical density, spacing of

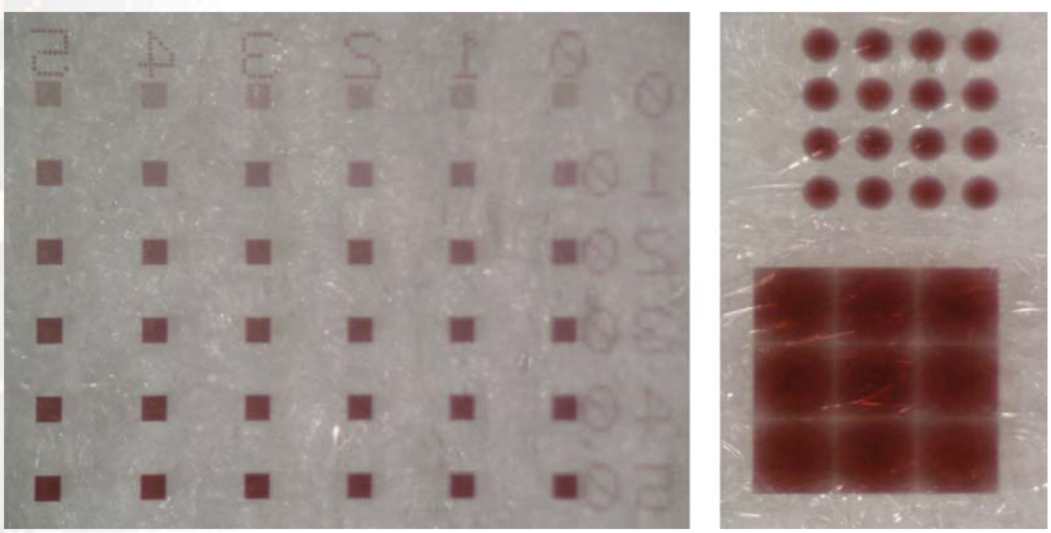

Figure 1. Calibration squares of varying optical density and micro-lens arrays on the HEBS glass gray-scale photomask.

gray levels, photoresist thickness, and photoresist development time; and
2. documentation of the process and parametric study for general use so that the LLNL microfabrication community at large can easily fabricate a microstructure with an arbitrary sloped surface.

Relevance to LLNL Mission

The ability to fabricate sloped surfaces at an arbitrary angle in silicon microsystems allows for a host of new geometries not previously considered, and will shift the overarching microfabrication paradigm away from 2-D structures. The availability of this technique will advance the core microfabrication competencies at LLNL, which provides vital support to both internal and external customers.

FY2006 Accomplishments and Results

High-energy beam-sensitive (HEBS) glass from Canyon Materials, Inc. was selected as the material for the photomask. HEBS glass is doped with a photoinhibitor that changes opacity when exposed to an electron beam. The change in optical density of the glass varies with the intensity of the beam, thus controlling the gray levels. The theoretical minimum feature size for a gray level is the thickness of the beam, and ~1000 discreet gray levels of varying optical density are possible. The photomask used in this work contained a variety of features intended to calibrate the gray-scale process in LLNL's cleanroom, and show some of the capabilities of the technique. Features included micro-lens arrays, grating structures, tapered structures of varying height, and calibration squares of varying height to correlate photoresist thickness to mask optical density. Figure 1 shows some of the features on the photomask.

Two types of photoresist were calibrated with the gray-scale mask. These included AZ4620 thick resist and AZ1518 thin resist. A range of thicknesses (~1 to 10 µm) of each of these photoresist types were spun onto silicon wafers, exposed to UV light, and developed. The photoresist profiles were then characterized using a SEM and an optical interferometer. Figure 2 shows interferometer measurements of photoresist profiles for the micro-lens features. By careful measurement of the remaining photoresist height, a calibration curve of resist thickness versus photomask optical density for a given set of process conditions was generated. These curves can then be used by engineers to design gray-scale photomasks for custom applications.

Finally, DRIE of the photoresist profiles was performed and 3-D features in the silicon substrates were obtained. Figures 3 and 4 show SEMs of the micro-lens arrays and the varying height calibration squares in silicon. The overall etch depths for these features were ~120 µm and the AZ4620 thick photoresist was used.

As a result of this work LLNL now has the capability to produce arbitrary, 3-D, sloped-surface microstructures for a variety of applications.

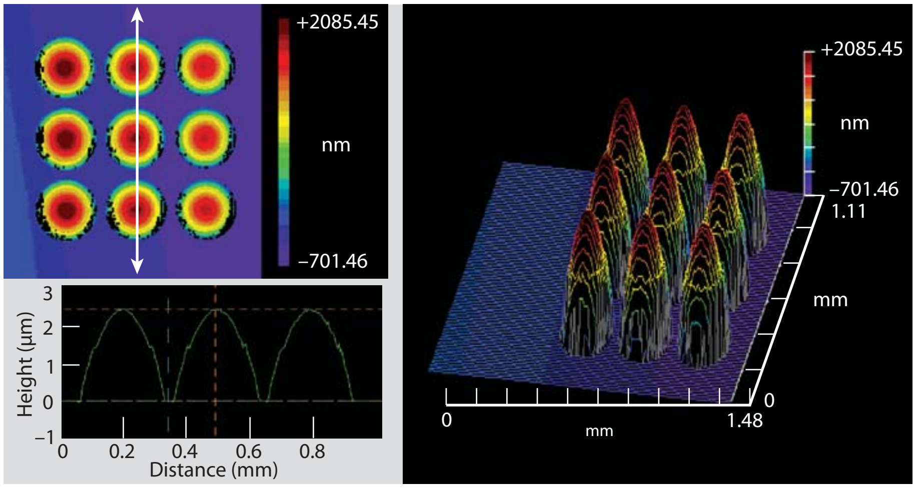

Figure 2. Optical interferometer measurement of micro-lens photoresist profiles.

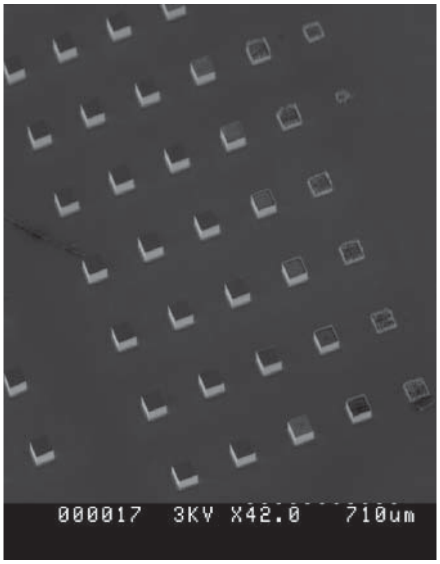

Figure 3. SEM of varying height calibration squares after DRIE in silicon.

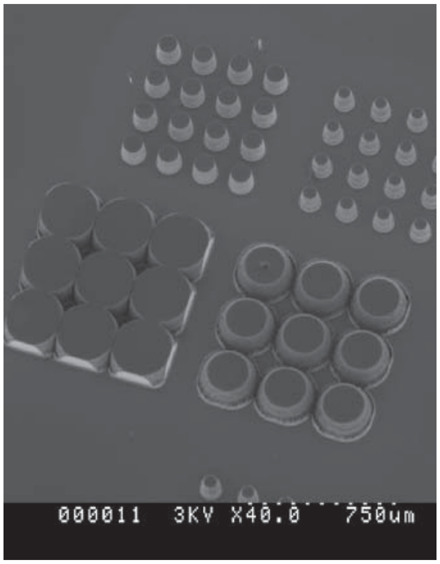

Figure 4. SEM of micro-lens arrays after DRIE in silicon.